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CMS Collaboration ; Khachatryan, V ; Amsler, C ; Chiochia, V

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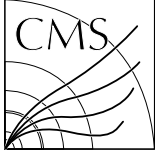
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Search for Pair Production of First-Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A search for pair production of first-generation scalar leptoquarks is performed in the final state containing two electrons and two jets using proton-proton collision data at $\sqrt{s} = 7$ TeV. The data sample used corresponds to an integrated luminosity of 33 pb^{-1} collected with the CMS detector at the CERN LHC. The number of observed events is in good agreement with the predictions for the standard model background processes, and an upper limit is set on the leptoquark pair production cross section times β^2 as a function of the leptoquark mass, where β is the branching fraction of the leptoquark decay to an electron and a quark. A 95% confidence level lower limit is set on the mass of a first-generation scalar leptoquark at 384 GeV for $\beta = 1$, which is the most stringent direct limit to date.

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*See Appendix A for the list of collaboration members

Although the standard model (SM) of fundamental particles and their interactions is in excellent agreement with most collider data, there are compelling reasons to believe new physics should appear at high energy scales. Some well-motivated theories of physics beyond the SM, including grand unified theories [1], composite models [2], technicolor [3–5], and superstring-inspired E_6 models [6], postulate the existence of a symmetry, beyond that of the SM, relating quarks and leptons and implying the existence of new bosons, called leptoquarks (LQ). An LQ carries colour, has fractional electric charge, can have spin 0 (scalar) or spin 1 (vector), and couples to a lepton and a quark with coupling strength λ . An LQ would decay to a charged lepton and a quark, with an unknown branching fraction β , or a neutrino and a quark, with branching fraction $1 - \beta$. A review of LQ phenomenology and searches can be found in [7, 8]. Constraints from experiments sensitive to flavour-changing neutral currents, lepton-family-number violation, and other rare processes [9] favour LQs that couple to quarks and leptons within the same SM generation, for LQ masses accessible at current colliders. The first-generation scalar LQs studied in this Letter couple only to an electron or an electron neutrino and a light quark. Measurements at electron-proton colliders constrain the coupling λ to be comparable to or less than the electromagnetic coupling $\lambda_{\text{EM}} \equiv \sqrt{4\pi\alpha_{\text{EM}}} \approx 0.3$, for a first generation LQ mass, M_{LQ} , less than 300 GeV [10, 11]. Prior to this work, the DØ Collaboration set the most stringent limit for a broad range of the coupling λ on the mass of the first-generation scalar LQ, namely, $M_{\text{LQ}} > 299$ GeV for $\beta = 1$ [12].

This Letter presents the results of a search for pair production of first-generation scalar LQs using events containing two electrons and two jets from a data sample of pp collisions at $\sqrt{s} = 7$ TeV collected in 2010 with the Compact Muon Solenoid (CMS) detector at the LHC. The data sample corresponds to an integrated luminosity of 33.2 ± 3.7 pb $^{-1}$. In pp collisions at this energy, LQs are predominantly produced in pairs via gluon-gluon fusion and quark-antiquark annihilation with a cross section that depends on the strong coupling constant α_s but is nearly independent of λ . This cross section depends on the spin and the mass of the LQ and has been calculated including Next-to-Leading-Order (NLO) Quantum Chromodynamics (QCD) corrections [13]. In this study we did not consider possible contributions from single LQ production, which has a cross section that is dependent on λ . The CMS experiment [14] uses a right-handed coordinate system, with the origin at the nominal interaction point, the x -axis pointing to the center of the LHC ring, the y -axis pointing up (perpendicular to the LHC plane), and the z -axis along the anticlockwise-beam direction. The polar angle, θ , is measured from the positive z -axis and the azimuthal angle, ϕ , is measured in the x - y plane. The pseudorapidity is given by $\eta = -\ln(\tan \theta/2)$. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), which includes a silicon sensor preshower detector in front of the ECAL endcaps, and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The ECAL has an ultimate energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The energy resolution is 3% or better for the range of electron energies relevant for this analysis. The HCAL, when combined with the ECAL, measures jets with a resolution $\Delta E/E \approx 100\%/\sqrt{E[\text{GeV}]} \oplus 5\%$. The inner tracker measures charged particles within $|\eta| < 2.5$ and provides an impact parameter resolution of ~ 15 μm and a transverse momentum (p_T) resolution of about 1.5% for 100 GeV particles. The relative luminosity is measured using the forward calorimeters. Collision events were selected by a first level trigger made of a system of fast electronics and a higher level trigger that consists of a farm of commercial CPUs running a version of the offline reconstruction optimized for fast processing.

Events used in this analysis are collected with an efficiency of 100% by single and double electron triggers with various thresholds depending on the instantaneous luminosity. Offline, events are required to contain at least one primary vertex with z -position within 24 cm of the nominal center of the detector. Electron candidates are required to have an electromagnetic cluster in ECAL that is spatially matched to a reconstructed track in the central tracking system in both η and ϕ . Electron candidates are further required to have a shower shape consistent with that of an electromagnetic shower, have a ratio between the hadronic and electromagnetic energy of less than 5%, and be isolated within a cone $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ from other energy deposits in the calorimeter and from additional reconstructed tracks (beyond the matched track) in the central tracking system. More information about electron triggering and identification at CMS can be found elsewhere [15]. Jets, the experimental signature of the hadronization of partons, are reconstructed in this analysis from calorimetry information by the anti- k_T algorithm [16] with the distance parameter set to 0.5. The energy response of the jets is adjusted by applying a correction determined from Monte Carlo (MC) simulated events and a residual correction derived from data by analyzing the p_T balance in di-jet events [17].

The collision data were compared to samples of MC generated events, where the response of the detector was simulated using GEANT4 [18]. The selection procedure as well as the electron and jet reconstructions described for the data are also applied to the MC simulation samples. Signal samples for LQ masses from 200 to 500 GeV were generated with PYTHIA [19], version 6.422, tune D6T [20, 21]. An initial sample containing at least two electrons and at least two jets is selected. The dominant SM processes that produce such events are Z/γ +jets and $t\bar{t}$, which are simulated, respectively, using ALPGEN [22] and MADGRAPH [23, 24] interfaced with PYTHIA for parton showering and hadronization. Other backgrounds include multijet production with two jets misidentified as electrons and W +jets events with one jet mis-identified as an electron. There is also a small contribution from di-boson and single top production. The two leading (in p_T) electrons and two leading jets are used in the analysis and, to reduce the backgrounds, required to have $p_T > 30$ GeV. Selected electrons and jets have pseudorapidities $|\eta| < 2.5$ and $|\eta| < 3.0$, respectively, and if any of the selected electrons are closer than $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ to any of the selected jets, the event is rejected. In addition, the preliminary requirements $M_{ee} > 50$ GeV and $S_T > 250$ GeV are applied, where M_{ee} is the di-electron invariant mass and S_T is defined as the sum of the magnitudes of the p_T of the two leading electrons and two leading jets. At this stage of the selection, referred to as pre-selection, there are sufficient data to compare with the MC predictions. Good data-MC agreement is observed in the shape of all kinematic distributions of the selected electrons and jets. Fig. 1 shows the M_{ee} and S_T distributions. The Z/γ +jets MC distributions have been normalized to the data at the Z boson mass, as described later.

To reduce the background from $Z \rightarrow ee$ production, a minimal value of M_{ee} well above the mass of the Z boson is required, and, to reduce all SM backgrounds, S_T is required to be large. While the LQ signal is expected to appear as a peak in the mass distribution of the electron-jet pairs, we find that the S_T variable is more powerful with the present statistics as it is not affected by combinatorics. The minimal values required for M_{ee} and S_T were optimized by minimizing the expected upper limit on the leptoquark cross section in the absence of an observed signal using a Bayesian approach [25, 26] that is well suited for counting experiments in the Poisson regime. The optimized lower value of M_{ee} is found to be 125 GeV for all the LQ hypotheses under test, while the lower value of S_T varies as indicated in Table 1. Table 1 shows the number of surviving events for MC signal, MC background and data samples after applying the full optimized selection. The reported product of signal selection efficiency and acceptance is estimated from MC simulated events. The product of the di-electron efficiency and acceptance, prior to

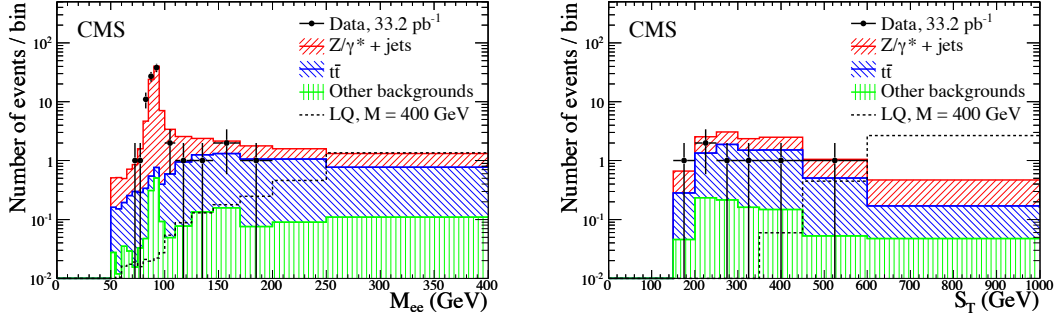


Figure 1: On the left: the M_{ee} distribution for events that have passed the pre-selection requirements. On the right: the S_T distribution for events that have passed the pre-selection requirement, except the pre-selection requirement on S_T itself ($S_T > 250$ GeV), and have $M_{ee} > 125$ GeV. The MC distributions for the signal ($\beta = 1$) and the contributing backgrounds are shown. The Z/γ +jets MC has been normalized as described in the text. Other backgrounds include W +jets, di-boson, and single top. All background histograms are cumulative.

any M_{ee} and jet requirements, varies from 58.7% to 68.0% for LQ masses from 200 to 500 GeV. The Z/γ +jets background dominates the pre-selection sample. After the pre-selection, the ratio

Table 1: Number of events for MC LQ signal (for $\beta = 1$), MC background, and data samples after the full analysis selection and corresponding to an integrated luminosity of 33.2 pb^{-1} . The product of signal acceptance and efficiency is also reported for different LQ masses. The Z/γ +jets MC has been normalized to the data at the Z boson mass as described in the text. Other backgrounds include W + jets, di-boson, and single top. Uncertainties are statistical. Systematic uncertainties are discussed later. The observed and expected 95% C.L. upper limit (u.l.) on the leptoquark pair production cross section σ are shown in the last column.

| M_{LQ} (S_T Cut) [GeV] | Signal Samples (MC) | | Standard Model Background Samples (MC) | | | | Events in Data | Obs./Exp. 95% C.L. u.l. on σ [pb] |
|-----------------------------------|---------------------|-----------------------------------|--|-------------------|-----------------|-----------------|----------------------|--|
| | Selected Events | Acceptance \times Efficiency | $t\bar{t}$ + jets | Z/γ + jets | Others | All | | |
| 200 ($S_T > 340$) | 117.5 \pm 0.8 | 0.297 \pm 0.002 | 2.2 \pm 0.09 | 2.0 \pm 0.2 | 0.27 \pm 0.05 | 4.5 \pm 0.2 | 2 | 0.445 / 0.692 |
| 250 ($S_T > 400$) | 43.8 \pm 0.2 | 0.380 \pm 0.002 | 1.1 \pm 0.06 | 1.3 \pm 0.1 | 0.14 \pm 0.02 | 2.5 \pm 0.1 | 1 | 0.311 / 0.442 |
| 280 ($S_T > 450$) | 24.4 \pm 0.1 | 0.403 \pm 0.002 | 0.59 \pm 0.05 | 0.87 \pm 0.07 | 0.10 \pm 0.02 | 1.6 \pm 0.1 | 1 | 0.309 / 0.361 |
| 300 ($S_T > 470$) | 17.3 \pm 0.1 | 0.430 \pm 0.002 | 0.44 \pm 0.04 | 0.75 \pm 0.07 | 0.10 \pm 0.02 | 1.3 \pm 0.1 | 1 | 0.294 / 0.326 |
| 320 ($S_T > 490$) | 12.3 \pm 0.1 | 0.451 \pm 0.002 | 0.37 \pm 0.04 | 0.65 \pm 0.07 | 0.08 \pm 0.02 | 1.1 \pm 0.1 | 1 | 0.285 / 0.299 |
| 340 ($S_T > 510$) | 8.88 \pm 0.04 | 0.469 \pm 0.002 | 0.27 \pm 0.03 | 0.56 \pm 0.06 | 0.08 \pm 0.02 | 0.91 \pm 0.08 | 1 | 0.279 / 0.274 |
| 370 ($S_T > 540$) | 5.55 \pm 0.02 | 0.496 \pm 0.002 | 0.22 \pm 0.03 | 0.47 \pm 0.06 | 0.07 \pm 0.02 | 0.76 \pm 0.07 | 1 | 0.268 / 0.251 |
| 400 ($S_T > 560$) | 3.55 \pm 0.02 | 0.522 \pm 0.002 | 0.17 \pm 0.02 | 0.41 \pm 0.05 | 0.06 \pm 0.02 | 0.64 \pm 0.06 | 1 | 0.259 / 0.230 |
| 450 ($S_T > 620$) | 1.70 \pm 0.01 | 0.539 \pm 0.002 | 0.10 \pm 0.02 | 0.28 \pm 0.05 | 0.02 \pm 0.01 | 0.40 \pm 0.06 | 0 | 0.174 / 0.209 |
| 500 ($S_T > 660$) | 0.868 \pm 0.003 | 0.565 \pm 0.002 | 0.07 \pm 0.02 | 0.23 \pm 0.05 | 0.02 \pm 0.01 | 0.32 \pm 0.05 | 0 | 0.166 / 0.193 |

between data and MC events with $80 < M_{ee} < 100$ GeV (where the contamination from other SM processes is 3%) is 1.20 ± 0.14 . This ratio is used to normalize the Z/γ +jets MC. The statistical uncertainty on this normalization factor is used as an uncertainty on the MC estimate of the Z/γ +jets background after the full selection. The $t\bar{t}$ background is estimated from MC with an uncertainty, 41%, taken from the uncertainty on the CMS measurement of the $t\bar{t}$ cross section [27]. Since this measurement is consistent with NLO predictions, no rescaling of the $t\bar{t}$ MC is applied. The small contribution from other background processes containing vector bosons is estimated by MC. The multijet background is determined from data. The probability that an isolated electromagnetic cluster is reconstructed as an electron is measured in a background sample requiring a single cluster, a jet multiplicity similar to the analysis final state, and small

missing transverse energy. This probability and a data sample with two or more of these clusters and two or more jets were used to determine the multijet contribution to the final selection sample. The resulting systematic uncertainty is determined to be 20%. This background accounts for $< 1\%$ of the total background for all LQ masses hypotheses with a decreasing trend for increasing LQ mass hypothesis, and is not considered any further.

The systematic uncertainties affecting the number of expected signal and background events are summarized in Table 2. The jet and electron energy scale uncertainties are given in the second column of Table 2. The reconstruction, identification, and isolation efficiency for electrons is determined from MC simulated events and a systematic uncertainty is assessed using $Z \rightarrow ee$ events from collision data. The statistical uncertainty on the number of MC events surviving the full event selection is reported in Table 1 for the signal and background. The uncertainty on the integrated luminosity of the data sample is dominated by the uncertainty on the measurement of the beam current [28]. Uncertainties due to the choice of parton distribution functions (PDF) of the proton lead to changes in the total cross section and the acceptance for both signal and background processes. The effect of the PDF uncertainties on the signal acceptance is estimated using an event re-weighting technique that uses the LHAPDF package [29] and amounts to 0.1%. Since a background normalization uncertainty is assessed based on data, uncertainties due to the PDF choice, electron efficiencies, and integrated luminosity are not applicable to the background estimate.

Table 2: Summary of the systematic uncertainties affecting the number of signal and background events for the hypothesis of LQ with mass of 300 GeV.

| Systematic Uncertainty | Magnitude [%] | Effect on Signal [%] | Effect on Background [%] |
|--------------------------------------|---------------|----------------------|--------------------------|
| Background Normalization Uncertainty | - | - | 21 |
| Jet Energy Scale | 5 | 3 | 11 |
| Electron Energy Scale Barrel/Endcap | 1/3 | 1 | 5 |
| Electron Pair Reco, ID, Iso | 10 | 10 | - |
| MC Statistics | - | 1 | 6 |
| Integrated Luminosity | 11 | 11 | - |
| Total | - | 15 | 25 |

The number of observed events in the collision data sample that pass the selection criteria optimized for each LQ mass considered is consistent with the prediction from SM processes, as reported in Table 1. An upper limit on the LQ cross section in the absence of signal is therefore set using a Bayesian approach [26] that uses a Poisson likelihood, a flat prior for the signal cross section, and log-normal priors for the parameters used to model the systematic uncertainties. Systematic uncertainties for the signal are dominated by the uncertainty on the integrated luminosity and the electron selection efficiencies, while the systematic uncertainties for the background are dominated by the uncertainty derived from data. Fig. 2 (left) shows the 95% Confidence Level (C.L.) upper limit on the LQ pair production cross section times β^2 as a function of the leptoquark mass for 33.2 pb^{-1} of integrated luminosity. The systematic uncertainties reported in Table 2 are included in the calculation. The upper limits are compared to an NLO prediction of the LQ pair production cross section [13] to set a 95% C.L. exclusion on LQ masses smaller than 384 GeV (expected 391 GeV), assuming $\beta = 1$. A theoretical uncertainty on the signal production cross sections due to the choice of renormalization/factorization scales (14-15% for all LQ masses considered) has been calculated by varying the scales between half and twice the LQ mass, while a 90% C.L. PDF uncertainty (from 8 to 22% for LQ masses from

200 to 500 GeV) has been obtained from the CTEQ6.6 error PDF set following the standard prescription detailed in Ref. [30]. If the observed cross section upper limit is compared with the lower boundary of the cross section uncertainty band, the lower limit on the LQ mass for $\beta = 1$ becomes 370 GeV (expected 375 GeV). Fig. 2 (right) shows the minimum β for a 95% C.L. exclusion of the LQ hypothesis as a function of LQ mass.

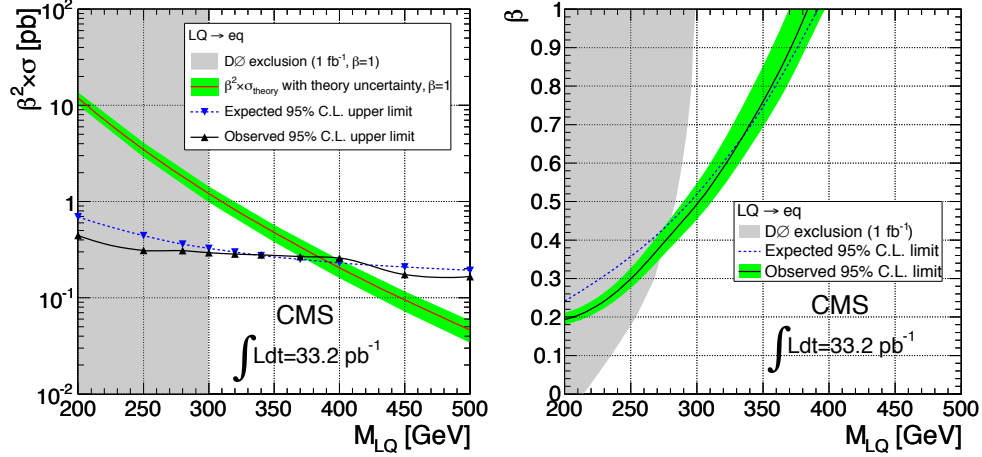


Figure 2: On the left: the expected and observed upper limit at 95% C.L. on the LQ pair production cross section times β^2 as a function of the LQ mass. The systematic uncertainties reported in Table 2 are included in the calculation. The shaded region is excluded by the current $D\bar{D}$ limit for $\beta = 1$. The σ_{theory} curve and its band represent, respectively, the theoretical LQ pair production cross section and the uncertainties due to the choice of PDF and renormalization/factorization scales [13]. On the right: minimum β for a 95% C.L. exclusion of the LQ hypothesis as a function of LQ mass. The observed (expected) exclusion curve is obtained using the observed (expected) upper limit and the central value of the theoretical LQ pair production cross section. The band around the observed exclusion curve is obtained by considering the observed upper limit while taking into account the uncertainties on the theoretical cross section. The shaded region is excluded by the current $D\bar{D}$ limits, which combines results from searches in the two electron, electron-neutrino, and two neutrino channels.

In conclusion, a search for pair production of first-generation scalar leptoquarks has been presented. The number of collision events, passing a selection optimized for exclusion of the LQ hypothesis, is in good agreement with the predictions for the SM background processes. A Bayesian approach that includes the treatment of the systematic uncertainties as nuisance parameters has been used to set an upper limit on the LQ cross section. By comparing this upper limit to a theoretical calculation of the LQ pair production cross section, the existence of first-generation scalar LQ with masses below 384 GeV for $\beta = 1$ has been excluded at 95% C.L., with a corresponding cross section limit of 0.267 pb. The lower limits on the LQ mass set for values of β larger than about 0.4 are the most restrictive direct limits to date. We wish to thank Michael Krämer for providing the NLO LQ pair production cross sections at $\sqrt{s} = 7$ TeV. We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häseler, C. Hartl, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

L. Benucci, L. Ceard, K. Cerny, E.A. De Wolf, X. Janssen, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

V. Adler, S. Beauceron, F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wickens

Ghent University, Ghent, Belgium

S. Costantini, M. Grunewald, B. Klein, A. Marinov, J. Mccartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, J. Caudron, J. De Favereau De Jeneret, C. Delaere, P. Demin, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Ovyn, D. Pagano, A. Pin, K. Piotrkowski, L. Quertenmont, N. Schul

Université de Mons, Mons, Belgium

N. Beliy, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, F. Torres Da Silva De Araujo

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

F.A. Dias, M.A.F. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores², F. Marinho, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

N. Darmanov¹, L. Dimitrov, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria

M. Dyulendarova, R. Hadjiiska, V. Kozhuharov, L. Litov, E. Marinova, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, J. Wang, J. Wang, X. Wang, Z. Wang, M. Xu, M. Yang, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

Y. Ban, S. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, B. Zhu

Universidad de Los Andes, Bogota, Colombia

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran⁴, M.A. Mahmoud⁵

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

A. Hektor, M. Kadastik, K. Kannike, M. Müntel, M. Raidal, L. Rebane

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola

Helsinki Institute of Physics, Helsinki, Finland

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, J. Klem, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Bianchini, M. Bluj⁶, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch⁷, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram⁸, J. Andrea, A. Besson, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte⁸, F. Drouhin⁸, C. Ferro, J.-C. Fontaine⁸, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim⁸, A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

C. Baty, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, H. Xiao

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia

V. Roinishvili

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, W. Bender, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, C. Hof, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], C. Magass, G. Masetti, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz⁹, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, I. Glushkov, J. Hauk, H. Jung, M. Kasemann, I. Katkov, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann⁹, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Parenti, A. Raspereza, A. Raval, R. Schmidt⁹, T. Schoerner-Sadenius, N. Sen, M. Stein, J. Tomaszewska, D. Volyanskyy, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, S. Bobrovskyi, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwandt, A.K. Srivastava, H. Stadie, G. Steinbrück, J. Thomsen, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, S.M. Heindl, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc,

T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, M. Zeise, V. Zhukov¹⁰, E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolagos, A. Markou, C. Markou, C. Mavrommatis, E. Petrakou

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou¹

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Aranyi, G. Bencze, L. Boldizsar, G. Debreczeni, C. Hajdu¹, D. Horvath¹¹, A. Kapusi, K. Krajczar¹², A. Laszlo, F. Sikler, G. Vesztergombi¹²

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, N. Dhingra, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J.B. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, S. Bhattacharya, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, A. Kumar, R.K. Shivpuri

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, S.K. Kataria, A.K. Mohanty¹, L.M. Pant, P. Shukla, P. Suggisetti

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait¹³, A. Gurtu, M. Maity¹⁴, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

Institute for Studies in Theoretical Physics & Mathematics (IPM), Tehran, Iran

H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammadi, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Dimitrov^a, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b,1}, G. Maggi^{a,c}, M. Maggi^a, N. Manna^{a,b}, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, G.A. Pierro^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, F. Romano^{a,c}, G. Roselli^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, R. Trentadue^a, S. Tupputi^{a,b}, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^a, S. Braibant-Giacomelli^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^a, P. Giacomelli^a, M. Giunta^a, S. Marcellini^a, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^a

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, C. Genta^a, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi¹⁵, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, A. Ghezzi^{a,b,1}, M. Malberti^{a,b}, S. Malvezzi^a, A. Martelli^{a,b}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}, V. Tancini^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^a, A. Cimmino^{a,b}, A. De Cosa^{a,b}, M. De Gruttola^{a,b}, F. Fabozzi^{a,16}, A.O.M. Iorio^a, L. Lista^a, M. Merola^{a,b}, P. Noli^{a,b}, P. Paolucci^a

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, E. Conti^a, M. De Mattia^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Fanzago^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, P. Giubileo^{a,b}, A. Gresele^{a,c}, S. Lacaprara^{a,17}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^a, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, P. Zotto^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

P. Baesso^{a,b}, U. Berzano^a, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}, C. Viviani^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, B. Caponeri^{a,b}, L. Fano^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, A. Santocchia^{a,b}, L. Servoli^a, S. Taroni^{a,b}, M. Valdata^{a,b}, R. Volpe^{a,b,1}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^{a,b}, T. Boccali^{a,1}, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^a, A. Messineo^{a,b}, F. Palla^a, F. Palmonari^a, S. Sarkar^{a,c}, G. Segneri^a, A.T. Serban^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b,1}, A. Venturi^{a,1}, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma "La Sapienza" ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, D. Franci^{a,b}, M. Grassi^a, E. Longo^{a,b}, G. Organtini^{a,b}, A. Palma^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Università del Piemonte Orientale (Novara) ^c, Torino, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, C. Botta^{a,b,1}, N. Cartiglia^a, R. Castello^{a,b}, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b,1}, C. Mariotti^a, M. Marone^{a,b}, S. Maselli^a, E. Migliore^{a,b}, G. Mila^{a,b}, V. Monaco^{a,b}, M. Musich^{a,b}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,b,1}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, D. Trocino^{a,b}, A. Vilela Pereira^{a,b,1}

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

F. Ambroglini^{a,b}, S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, D. Montanino^{a,b}, A. Penzo^a

Kangwon National University, Chunchon, Korea

S.G. Heo

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, D. Son, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

Zero Kim, J.Y. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, B. Hong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

University of Seoul, Seoul, Korea

M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigalionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla Valdez, E. De La Cruz Burelo, R. Lopez-Fernandez, A. Sánchez Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

P. Allfrey, D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, R. Doesburg, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Martins, P. Musella, A. Nayak, P.Q. Ribeiro, J. Seixas, P. Silva, J. Varela¹, H.K. Wöhri

Joint Institute for Nuclear Research, Dubna, Russia

I. Belotelov, P. Bunin, M. Finger, M. Finger Jr., I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia

N. Bondar, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov¹, A. Krokhotin, N. Lychkovskaya, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin¹⁸, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, S. Slabospitsky, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic¹⁹, M. Djordjevic, D. Krpic¹⁹, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, C. Diez Pardos, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, M. Chamizo Llatas, S.H. Chuang, J. Duarte Campderros, M. Felcini²⁰, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez²¹, T. Rodrigo, A. Ruiz Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell²², D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, H. Breuker, G. Bruna, K. Bunkowski, T. Camporesi, E. Cano, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, F. Duarte Ramos, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, S. Gennai, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, J. Harvey, J. Hegeman, B. Hegner, C. Henderson, G. Hesketh, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, E. Karavakis, P. Lecoq, C. Leonidopoulos, C. Lourenço, A. Macpherson, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, G. Rolandi²³, T. Rommerskirchen, C. Rovelli²⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas²⁵, D. Spiga, M. Spiropulu¹⁸, F. Stöckli, M. Stoye, P. Tropea, A. Tsirou, A. Tsyganov, G.I. Veres¹², P. Vichoudis, M. Voutilainen, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille²⁶, A. Starodumov²⁷

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

P. Bortignon, L. Caminada²⁸, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica²⁸, P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic²⁹, F. Moortgat, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny²⁰, M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek, L. Wilke

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, W.T. Chen, S. Dutta, A. Go, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.K. Liu, Y.J. Lu, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci, S. Cerci³⁰, Z. Demir, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut³¹, B. Tali, H. Topakli, D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

M. Deliomeroglu, D. Demir³², E. Gülmez, A. Halu, B. Isildak, M. Kaya³³, O. Kaya³³, S. Ozkorucuklu³⁴, N. Sonmez³⁵

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

P. Bell, F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, B. Huckvale, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold³⁶, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso, K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, J. Fulcher, D. Futyan, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, R. Nandi, J. Nash, A. Nikitenko²⁷, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi³⁷, D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, D. Wardrobe, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, USA

K. Hatakeyama

Boston University, Boston, USA

T. Bose, E. Carrera Jarrin, A. Clough, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, M. Segala, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

M.A. Borgia, R. Breedon, M. Calderon De La Barca Sanchez, D. Cebra, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, A. Luthra, H. Nguyen, G. Pasztor³⁸, A. Satpathy, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, E. Dusinger, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, J. Muelmenstaedt, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma¹, S. Simon, Y. Tu, A. Vartak, F. Würthwein, A. Yagil

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant

California Institute of Technology, Pasadena, USA

A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, D. Kcira, V. Litvine, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, N. Terentyev, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA

L. Agostino, J. Alexander, A. Chatterjee, S. Das, N. Eggert, L.J. Fields, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, V. Kuznetsov, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, D. Riley, A. Ryd, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borchering, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Demarteau, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, E. James, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Kilminster, B. Klima, K. Kousouris, S. Kunori, S. Kwan, P. Limon, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. McCauley, T. Miao, K. Mishra, S. Mrenna, Y. Musienko³⁹, C. Newman-Holmes, V. O'Dell, S. Popescu⁴⁰, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, B. Kim, S. Klimenko, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, Y. Pakhotin, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, USA

C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, D. Bandurin, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopyanov

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, E.J. Garcia-Solis, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki, K. Cankocak⁴¹, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, M. Murray, D. Noonan, V. Radicci, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA

T. Bolton, I. Chakaberia, A. Ivanov, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

A. Baden, M. Boutemour, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

P. Cole, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Duerdo, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Mississippi, University, USA

L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, C. Lundstedt, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

U. Baur, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, K. Kaadze, S. Reucroft, J. Swain, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

L. Antonelli, D. Berry, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, J. Warchol, M. Wayne, J. Ziegler

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, Z. Gece, L. Gutay, Z. Hu, M. Jones, O. Koybasi, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, K. Potamianos, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

P. Jindal, N. Parashar

Rice University, Houston, USA

C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, J.H. Liu, J. Morales, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher,

A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian, M. Yan

Rutgers, the State University of New Jersey, Piscataway, USA

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

J. Asaadi, R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, C.N. Nguyen, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, USA

N. Akchurin, C. Bardak, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, USA

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, M. Buehler, S. Conetti, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton¹, M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, D. Lomidze, R. Loveless, A. Mohapatra, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased

1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

2: Also at Universidade Federal do ABC, Santo Andre, Brazil

3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

4: Also at Suez Canal University, Suez, Egypt

5: Also at Fayoum University, El-Fayoum, Egypt

6: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland

7: Also at Massachusetts Institute of Technology, Cambridge, USA

8: Also at Université de Haute-Alsace, Mulhouse, France

9: Also at Brandenburg University of Technology, Cottbus, Germany

10: Also at Moscow State University, Moscow, Russia

11: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

12: Also at Eötvös Loránd University, Budapest, Hungary

13: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India

14: Also at University of Visva-Bharati, Santiniketan, India

- 15: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
- 16: Also at Università della Basilicata, Potenza, Italy
- 17: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 18: Also at California Institute of Technology, Pasadena, USA
- 19: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 20: Also at University of California, Los Angeles, Los Angeles, USA
- 21: Also at University of Florida, Gainesville, USA
- 22: Also at Université de Genève, Geneva, Switzerland
- 23: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 24: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 25: Also at University of Athens, Athens, Greece
- 26: Also at The University of Kansas, Lawrence, USA
- 27: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 28: Also at Paul Scherrer Institut, Villigen, Switzerland
- 29: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 30: Also at Adiyaman University, Adiyaman, Turkey
- 31: Also at Mersin University, Mersin, Turkey
- 32: Also at Izmir Institute of Technology, Izmir, Turkey
- 33: Also at Kafkas University, Kars, Turkey
- 34: Also at Suleyman Demirel University, Isparta, Turkey
- 35: Also at Ege University, Izmir, Turkey
- 36: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 37: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 38: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- 39: Also at Institute for Nuclear Research, Moscow, Russia
- 40: Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- 41: Also at Istanbul Technical University, Istanbul, Turkey